

# SEMICONDUCTOR DEVICE AND METHOD FOR PRODUCING THE SAME

## BACKGROUND OF THE INVENTION

a The present invention relates to a semiconductor device, <sup>and,</sup>  
a in particular, to ~~that with~~ <sup>a semiconductor device having a</sup> layered interconnect structure.

a In recent large-scale-integration, <sup>for</sup> high-performance  
semiconductor devices, copper (Cu) interconnects are being  
a <sup>since they have a</sup> ~~employed as having~~ <sup>electrical</sup> lower electric resistance than conventional  
aluminum (Al) interconnects. However, diffusion of copper

a (Cu) atoms into silicon (Si) substrates or insulating films ~~will~~  
<sup>tends to degrade</sup> ~~detract from~~ the characteristics of <sup>such</sup> ~~the~~ devices. To prevent

a <sup>such</sup> ~~the~~ copper (Cu) diffusion, a diffusion barrier is formed  
adjacent to the copper (Cu) film. As the material for the  
diffusion barrier, high-melting-point metal films of, for  
example, titanium nitride (TiN), tungsten (W) or tantalum (Ta)  
a have been investigated, as <sup>discussed</sup> ~~in~~ the Nikkei Microdevice (for July  
1992, pp. 74-77).

a Large-scale-integration semiconductor devices with fine  
patterns receive <sup>a</sup> high-density current, in which, therefore,

a atoms are diffused owing to electron streams flowing therein  
and to <sup>the</sup> ~~heat as~~ <sup>that is</sup> generated by the flow <sup>of electrons, thereby</sup> to cause voids and

a interconnect breakdowns. The problem with the devices is <sup>the result of</sup>  
so-called electromigration. As compared with aluminum (Al)  
a films, copper (Cu) films, <sup>which have</sup> ~~as having~~ a higher melting point, are  
difficult to diffuse, and are therefore expected to have good

electromigration resistance. However, layered interconnect structures, in which a diffusion barrier of, for example, a titanium nitride (TiN) film, a tungsten (W) film or a tantalum (Ta) film, is kept in contact with a copper (Cu) film ~~could~~<sup>do</sup> not have<sup>a</sup> satisfactory electromigration resistance, and therefore often pose the problem of voids and interconnect breakdowns.

#### SUMMARY OF THE INVENTION

Given <sup>the above-described</sup> ~~that~~ situation, the object of the invention is to provide a reliable semiconductor device with a layered interconnect structure that ~~may~~<sup>will</sup> develop no trouble<sup>in the form</sup> of voids and interconnect breakdowns.

We, the present inventors, have clarified that, in a layered interconnect structure where a diffusion barrier of, for example, a titanium nitride (TiN) film, a tungsten (W) film or a tantalum (Ta) film is kept in contact with a copper (Cu) film, the significant difference between the material of the diffusion barrier material and copper (Cu) in the length of the sides of the unit cell brings about<sup>a</sup> a disordered atomic configuration in the interface therebetween, thereby promoting copper diffusion that results in the ~~trouble~~<sup>problem</sup> of voids and interconnect breakdowns. Therefore, in order to prevent the voids and breakdowns in copper (Cu) interconnects, a material that differs little from copper (Cu) in the length of the sides of the unit cell ~~shall~~<sup>should</sup> be used for the film to be disposed

a adjacent to the copper (Cu) film, thereby inhibiting the copper diffusion. We have further clarified that, in a layered interconnect structure comprising a conductor film and a neighboring film as layered adjacent to the conductor film, when the difference between the short side,  $a_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film and the short side,  $a_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring film,  $\{|a_p - a_n|/a_p\} \times 100 = A (\%)$ , is smaller than 13 %, and when the difference between the long side,  $b_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film and the long side,  $b_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring film,  $\{|b_p - b_n|/b_p\} \times 100 = B (\%)$ , as multiplied by  $(a_p/b_p)$ , is smaller than 13, then the diffusion of the conductor film is retarded, thereby to prevent voids and interconnect breakdowns. In addition, we have still further clarified that, especially when A and B satisfy an inequality of  $\{A + B \times (a_p/b_p)\} < 13$ , preferred results are obtained. The definitions of the short side, a, and the long side, b, in rectangular unit cells as referred to herein are illustrated in Fig. 6.

a Therefore, the object of the invention noted above is attained by a semiconductor device with a layered interconnect structure comprising a conductor film and a neighboring film

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platinum (Pt) film, wherein the neighboring film is any of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film or an osmium (Os) film.

Concretely, preferred embodiments of the invention are as follows:

a A semiconductor device with a layered structure comprising a copper (Cu) film interconnect formed on one primary surface of a semiconductor substrate, and a diffusion barrier formed in contact with the copper (Cu) film interconnect, wherein the diffusion barrier is <sup>formed</sup> of a ruthenium (Ru) film, and the copper (Cu) film interconnect has a layered structure comprising a copper (Cu) film as formed through sputtering and a copper (Cu) film as formed through plating.

a A semiconductor device with a layered structure comprising a copper (Cu) film interconnect formed on one primary surface of a semiconductor substrate, and a diffusion barrier formed in contact with the copper (Cu) film interconnect, wherein the diffusion barrier is <sup>formed</sup> of a ruthenium (Ru) film, and the copper (Cu) film interconnect has a layered structure comprising a copper (Cu) film as formed through physical vapor deposition (PVD) and a copper (Cu) film as formed through chemical vapor deposition (CVD).

A semiconductor device with a layered structure comprising a copper (Cu) film interconnect formed on one primary surface of a semiconductor substrate, and a diffusion barrier formed

a in contact with the copper (Cu) film interconnect, wherein the diffusion barrier is <sup>formed</sup> of a sputter-deposited ruthenium (Ru) film, and the copper (Cu) film interconnect has a layered structure comprising a copper (Cu) film as formed through sputtering and a copper (Cu) film as formed through plating or chemical vapor deposition (CVD).

a A semiconductor device with a structure comprising a copper (Cu) film interconnect formed on one primary surface of a semiconductor substrate, and a plug formed in contact with the copper (Cu) film interconnect, wherein the plug is <sup>formed</sup> of at least one film selected from the group consisting of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film, an osmium (Os) film and a platinum (Pt) film, and at least one of the copper (Cu) film interconnect and the plug contains a layer as formed through physical vapor deposition (PVD).

a A semiconductor device with a structure comprising a copper (Cu) film interconnect formed on one primary surface of a semiconductor substrate, a diffusion barrier formed in contact with the copper (Cu) film interconnect, and a plug formed in contact with the diffusion barrier, wherein the diffusion barrier is <sup>formed</sup> of a ruthenium (Ru) film, the plug is <sup>formed</sup> of a ruthenium (Ru) film, and at least one of the copper (Cu) film interconnect and the plug contains a layer as formed through physical vapor deposition (PVD).

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A semiconductor device with a structure comprising a copper (Cu) film interconnect formed on one primary surface of a semiconductor substrate, a first diffusion barrier formed in contact with the copper (Cu) film interconnect, a plug formed in contact with the first diffusion barrier, and a second diffusion barrier formed in contact with the plug and the first diffusion barrier, wherein the first diffusion barrier is <sup>Formed</sup> of a ruthenium (Ru) film, the plug is <sup>Formed</sup> of a ruthenium (Ru) film, the second diffusion barrier is <sup>Formed</sup> of a titanium nitride (TiN) film, and at least one of the copper (Cu) film interconnect and the first diffusion barrier is ~~of~~ a film ~~as~~ formed through sputtering.

A semiconductor device with a structure comprising a platinum (Pt) electrode film formed on one primary surface of a semiconductor substrate, and a neighboring film formed in contact with the platinum (Pt) electrode film, wherein the neighboring film is at least one film selected from the group consisting of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film and an osmium (Os) film, and at least one of the platinum (Pt) electrode film and the neighboring film is of a film as formed through sputtering.

A method for producing semiconductor devices, which comprises the following steps:

a step of forming a ruthenium (Ru) film on one primary surface of a semiconductor substrate through sputtering;

a a step of forming a first copper (Cu) film ~~to be~~ in contact with the ruthenium (Ru) film, through sputtering; and

a a step of forming a second copper (Cu) film ~~to be~~ in contact with the first copper (Cu) film, through plating or chemical vapor deposition (CVD).

#### BRIEF DESCRIPTION OF THE DRAWINGS

a a Fig. 1 is a cross-sectional view showing a layered interconnect structure of a semiconductor device, <sup>according to a</sup> ~~of the~~ first embodiment of the invention;

Fig. 2 is a graph indicating the effect of neighboring film materials on a conductor film of copper (Cu), relative to the diffusion coefficient of the copper (Cu) film;

Fig. 3 is a characteristic curve indicating the effect of neighboring film materials on a conductor film of copper (Cu), relative to the diffusion coefficient of the copper (Cu) film along the dotted line in Fig. 2;

a Fig. 4 is a ~~characteristic~~ graph indicating the effect of neighboring film materials on a conductor film of platinum (Pt), relative to the diffusion coefficient of the platinum (Pt) film;

Fig. 5 is a characteristic curve indicating the effect of neighboring film materials on a conductor film of platinum (Pt), relative to the diffusion coefficient of the platinum (Pt) film along the dotted line in Fig. 4;



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Fig. 6 is a <sup>diagram</sup> ~~a view~~ showing the atomic configuration in rectangular unit cells, and the short side and the long side of each unit cell;

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Fig. 7 is a cross-sectional view showing a layered interconnect structure of a semiconductor device <sup>according to a</sup> ~~of the second~~ embodiment of the invention;

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Fig. 8 is a cross-sectional view showing the principal part of ~~a semiconductor device of the~~ <sup>according to a</sup> third embodiment of the invention; and

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Fig. 9 is a cross-sectional view showing the principal part with a preferred functional structure <sup>the</sup> ~~of a semiconductor device~~ of the third embodiment of the invention.

#### DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

Embodiments of the invention are described hereinunder with reference to the drawings.

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~~First referred to is~~ Fig. 1, <sup>view of the</sup> ~~which~~ shows a cross-sectional structure of the layered interconnect ~~structure~~ part of a semiconductor device <sup>according to</sup> ~~of the first~~ embodiment of the invention.

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As <sup>seen</sup> in Fig. 1, the layered interconnect structure in the semiconductor device of this embodiment comprises an insulating film 2 of, for example, silicon oxide as formed on a silicon substrate 1, in which a first layered interconnect structure 6, composed of a neighboring film 3, a conductor film 4 and a neighboring film 5, is connected with the substrate 1 via a

contact hole ~~as~~ formed through the insulating film 2. ~~In this,~~  
<sup>A<sub>n</sub></sup>  
~~an~~ insulating film 7 of, for example, silicon oxide is formed  
 on the first layered interconnect structure 6, and a via 8 of,  
 for example, tungsten (W)<sub>λ</sub> is filled in <sup>a</sup>~~the~~ via hole ~~as~~ formed  
 through the insulating film 7. Through this via 8, a second  
 layered interconnect structure 12<sub>λ</sub> composed of a neighboring  
 film 9, a conductor film 10 and a neighboring film 11<sub>λ</sub> is connected  
 with the first layered interconnect structure 6. The first  
 layered interconnect structure 6 is characterized in that the  
 neighboring film 3, the conductor film 4 and the neighboring  
 film 5 are formed of a combination of materials satisfying an  
 inequality of  $\{A + B \times (a_p/b_p)\} < 13$ , where A indicates the  
 difference between the short side,  $a_p$ , of the rectangular unit  
 cells that constitute the plane with minimum free energy of the  
 conductor film 4 and the short side,  $a_n$ , of the rectangular unit  
 cells that constitute the plane with minimum free energy of the  
 neighboring films 3, 5, and is represented as  $\{|a_p - a_n|/a_p\} \times$   
 $100 = A (\%)$ , and B indicates the difference between the long  
 side,  $b_p$ , of the rectangular unit cells that constitute the plane  
 with minimum free energy of the conductor film 4 and the long  
 side,  $b_n$ , of the rectangular unit cells that constitute the plane  
 with minimum free energy of the neighboring films 3, 5, and is  
 represented as  $\{|b_p - b_n|/b_p\} \times 100 = B (\%)$ . Concretely, where  
 the conductor film 4 is a copper (Cu) film, the neighboring films  
 3, 5 could be any of a rhodium (Rh) film, a ruthenium (Ru) film,

an iridium (Ir) film, an osmium (Os) film and a platinum (Pt) film. Where the conductor film 4 is a platinum (Pt) film, the neighboring films 3, 5 could be any of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film and an osmium (Os) film.

9 *Similarly*  
^ ~~like this~~, the second layered interconnect structure 12 is characterized in that the neighboring film 9, the conductor film 10 and the neighboring film 11 are formed of a combination of materials satisfying an inequality of  $\{A + B \times (a_p/b_p)\} < 13$ , where A indicates the difference between the short side,  $a_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film 10 and the short side,  $a_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring films 9, 11, and is represented as  $\{|a_p - a_n|/a_p\} \times 100 = A (\%)$ , and B indicates the difference between the long side,  $b_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film 10 and the long side,  $b_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring films 9, 11, and is represented as  $\{|b_p - b_n|/b_p\} \times 100 = B (\%)$ . Concretely, where the conductor film 10 is a copper (Cu) film, the neighboring films 9, 11 could be any of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film, an osmium (Os) film and a platinum (Pt) film. Where the conductor film 10 is a platinum (Pt) film, the neighboring films 9, 11 could

be any of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film and an osmium (Os) film.

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a The effect of the semiconductor device of this embodiment <sup>will be</sup> ~~is~~ described below.

a We, the ~~inventors~~ <sup>have</sup> specifically noticed the difference between the conductor film and the neighboring film in the short side, a, and the long side, b, of the rectangular unit cells that constitute the plane with minimum free energy of those films, <sup>and we have</sup> ~~and~~ investigated the influence of this difference on the diffusion coefficient of the conductor film through computer simulation. Concretely, for the layered interconnect structure comprising a conductor film and a neighboring film ~~as~~ so layered that the two are in contact with each other, <sup>was prepared in which represented</sup> ~~prepared was a map where~~ the abscissa ~~indicates~~ the difference between the short side,  $a_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film and the short side,  $a_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring film,  $\{|a_p - a_n|/a_p\} \times 100 = A (\%)$ , and the ordinate <sup>represented</sup> ~~indicates~~ the difference between the long side,  $b_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film and the long side,  $b_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring film,  $\{|b_p - b_n|/b_p\} \times 100 = B (\%)$ , as multiplied by  $(a_p/b_p)$ . Based on the data of A and B as defined to cover

the map, the value of the diffusion coefficient of the conductor film was calculated through computer simulation.

First, <sup>a</sup> ~~conducted was the~~ simulation <sup>was conducted</sup> for a conductor film of copper (Cu) at a temperature of 700K. Copper (Cu) has the face-centered cubic (fcc) structure, and the plane with minimum free energy of copper (Cu) is the (111) plane. The simulation data <sup>For</sup> of this case are shown in Fig. 2, in which the diffusion coefficient of the copper (Cu) film greatly increases in the upper region as separated by the boundary line. In the lower region as separated by the boundary line, which is near to the origin of the coordinate axes, the diffusion coefficient is small and voids are hardly formed, while in the upper region as separated by it, the diffusion coefficient is large and voids are easily formed. To check this aspect in detail, the diffusion coefficient of the copper (Cu) film was investigated along the dotted line in Fig. 2, and the <sup>results</sup> ~~data~~ are shown in Fig. 3. In Fig. 3,  $D$  indicates the diffusion coefficient of the copper (Cu) film, and  $D_0$  indicates the diffusion coefficient of copper (Cu) in bulk. In this, it is known that the diffusion coefficient greatly increases in the right-hand region as separated by the boundary line, in which titanium nitride (TiN) and <sup>other materials</sup> ~~others~~ used in conventional neighboring films are positioned. Referring back to Fig. 2, it is known that the tungsten (W) film and the tantalum (Ta) film are also in the upper region above the boundary line. On the other hand, in

Fig. 2, the rhodium (Rh) film, the ruthenium (Ru) film, the  
 iridium (Ir) film, the osmium (Os) film and the platinum (Pt)  
 film are all positioned in the lower region below the boundary  
 line, ~~or~~ that is, in the region near to the origin of the  
 coordinate axes, and it is known that these films are effective  
 for preventing the copper (Cu) film from diffusion. The  
 materials of those films are all within the region in which both  
 A and  $B \times (a_p/b_p)$  are smaller than 13 %. Linear approximation  
 to the boundary line in Fig. 2 gives  $\{A + B \times (a_p/b_p)\} = 13$ .  
 Therefore, in the structure composed of a conductor film and  
 a neighboring film as formed of a combination of materials that  
 satisfies the inequality of  $\{A + B \times (a_p/b_p)\} < 13$ , copper  
 diffusion is retarded and voids and interconnect breakdowns are  
 thereby prevented. In this, the diffusion coefficient of the  
 copper (Cu) film is specifically noticed and it is judged that  
 voids are hardly formed in the copper (Cu) film with a smaller  
 diffusion coefficient. Also in neighboring films, it is  
<sup>desirable</sup>  
~~desired~~ that the voids are hardly formed. For this, it is more  
<sup>when</sup>  
 desirable ~~that~~ the neighboring films are made of a material  
 having a high melting point. For example, more preferred <sup>materials</sup>  
 for the neighboring films are rhodium (having a melting point of  
 1,960°C), ruthenium (having a melting point of 2,310°C), iridium  
 (having a melting point of 2,443°C) and osmium (having a melting  
<sup>as compared to</sup>  
 point of 3,045°C) to platinum (having a melting point of 1,769°C),  
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a since the melting <sup>points</sup> ~~point~~ of the former <sup>materials are</sup> ~~is~~ all higher than that of platinum.

a Next ~~conducted was the~~ <sup>a</sup> simulation <sup>was conducted</sup> for a conductor film of platinum (Pt). Like copper (Cu), platinum (Pt) has <sup>a</sup> ~~the~~ face-centered cubic (fcc) structure, and the plane with minimum free energy of platinum (Pt) is the (111) plane. The simulation data <sup>for</sup> ~~of~~ this case are shown in Figs. 4 and 5. The same <sup>Factors</sup> ~~as~~ in Fig. 2 shall apply to the data in Fig. 4. Also in Fig. 4, in the lower region as separated by the boundary line, which is near to the origin of the coordinate axes, the diffusion coefficient is small and voids are hardly formed, while in the upper region as separated by it, the diffusion coefficient is large and voids are easily formed. To check this aspect in detail, the diffusion coefficient of the platinum (Pt) film was investigated along the dotted line in Fig. 4, and the data are shown in Fig. 5. In Fig. 5,  $D$  indicates the diffusion coefficient of the platinum (Pt) film, and  $D_0$  indicates the diffusion coefficient of platinum (Pt) in bulk. In this, it is known that the diffusion coefficient greatly increases in the right-hand region as separated by the boundary line. Referring back to Fig. 4, it is known that the rhodium (Rh) film, the ruthenium (Ru) film, the iridium (Ir) film and the osmium (Os) film are all positioned in the lower region below the boundary line. This means that the materials for these films are effective for preventing the platinum (Pt) film from

diffusion. Those materials are all within the region in which both A and  $B \times (a_p/b_p)$  are smaller than 13 %. It is understood that the position of the boundary line in Fig. 4 well corresponds to that of the boundary line for the copper (Cu) film noted above. Linear approximation to those boundary lines gives  $\{A + B \times (a_p/b_p)\} = 13$ . Therefore, in the structure composed of a conductor film and a neighboring film as formed of a combination of materials that satisfies the inequality of  $\{A + B \times (a_p/b_p)\} < 13$ , conductor film diffusion is retarded and voids and interconnect breakdowns are thereby prevented.

reference is made  
Next ~~referred to~~ <sup>is</sup> Fig. 7, which shows a cross-sectional structure of a layered interconnect structure part of a semiconductor device <sup>according to</sup> ~~of the~~ second embodiment of the invention.

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As in Fig. 7, the layered interconnect structure in the semiconductor device of this embodiment comprises an insulating film 2 of, for example, silicon oxide ~~as~~ formed on a silicon substrate 1, in which a first layered interconnect structure 6 composed of a diffusion barrier 13, a neighboring film 3, a conductor film 4, a neighboring film 5 and a diffusion barrier 14 is connected with the substrate 1 via a contact hole ~~as~~ formed through the insulating film 2. <sup>An</sup> ~~In this, an~~ insulating film 7 of, for example, silicon oxide is formed on the first layered interconnect structure 6, and a via 8 of, for example, tungsten (W) is filled in the via hole ~~as~~ formed through the insulating film 7. Through this via 8, a second layered interconnect



structure 12<sub>Λ</sub> composed of a diffusion barrier 15, a neighboring film 9, a conductor film 10, a neighboring film 11 and a diffusion barrier 16<sub>Λ</sub> is connected with the first layered interconnect structure 6. The diffusion barriers 13, 14, 15, 16 comprise, for example, titanium nitride (TiN), tungsten (W), tantalum (Ta) or the like. The first layered interconnect structure 6 is characterized in that the neighboring film 3, the conductor film 4 and the neighboring film 5 are formed of a combination of materials satisfying an inequality of  $\{A + B \times (a_p/b_p)\} < 13$ , where A indicates the difference between the short side,  $a_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film 4 and the short side,  $a_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring films 3, 5, and is represented as  $\{|a_p - a_n|/a_p\} \times 100 = A (\%)$ , and B indicates the difference between the long side,  $b_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film 4 and the long side,  $b_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring films 3, 5, and is represented as  $\{|b_p - b_n|/b_p\} \times 100 = B (\%)$ . Concretely, where the conductor film 4 is a copper (Cu) film, the neighboring films 3, 5 could be any of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film, an osmium (Os) film and a platinum (Pt) film. Where the conductor film 4 is a platinum (Pt) film, the neighboring films 3, 5 could be

any of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film and an osmium (Os) film.

a <sup>Similarly</sup> ~~Like this~~, the second layered interconnect structure 12 is characterized in that the neighboring film 9, the conductor film 10 and the neighboring film 11 are formed of a combination of materials satisfying an inequality of  $\{A + B \times (a_p/b_p)\} < 13$ , where A indicates the difference between the short side,  $a_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film 10 and the short side,  $a_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring films 9, 11, and is represented as  $\{|a_p - a_n|/a_p\} \times 100 = A (\%)$ , and B indicates the difference between the long side,  $b_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film 10 and the long side,  $b_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring films 9, 11, and is represented as  $\{|b_p - b_n|/b_p\} \times 100 = B (\%)$ . Concretely, where the conductor film 10 is a copper (Cu) film, the neighboring films 9, 11 could be any of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film, an osmium (Os) film and a platinum (Pt) film. Where the conductor film 10 is a platinum (Pt) film, the neighboring films 9, 11 could be any of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film and an osmium (Os) film.

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Next ~~referred~~<sup>1</sup> to ~~is~~<sup>1</sup> Fig. 8, which shows a cross-sectional structure of a principal part of a semiconductor device, <sup>according to</sup> ~~of~~ the third embodiment of the invention. As in Fig. 8, the semiconductor device of this embodiment comprises diffusion layers 102, 103, 104, 105 all formed on a silicon substrate 101, on which are formed gate-insulating films 106, 107 and gate electrodes 108, 109 to construct MOS transistors. The gate-insulating films 106, 107 are, for example, silicon oxide films or silicon nitride films; and the gate electrodes 108, 109 are, for example, polycrystalline silicon films, thin metal films or metal silicide films, or are of a layered structure comprising any of them. The MOS transistors are separated from each other by an isolation film 110 of, for example, a silicon oxide film. The gate electrodes 108, 109 are covered with insulating films 111, 112, respectively, <sup>Formed</sup> ~~of~~<sup>1</sup>, for example, silicon oxide films, entirely on their top and side surfaces. The MOS transistors are entirely covered with an insulating film 113, which may be, for example, a BPSG (boron-doped phosphosilicate glass) or SOG (spin on glass) film or with a silicon oxide or nitride film as formed through chemical vapor deposition (CVD) or physical vapor deposition (PVD). In each contact hole ~~as~~ formed through the insulating film 113, <sup>Formed</sup> ~~formed~~<sup>1</sup> is a plug <sup>of</sup> a conductor film 115 which is in contact with neighboring films 114a, 114b <sup>the</sup> ~~of~~<sup>1</sup> diffusion barriers. The plugs are connected with the diffusion layers 102, 103, 104, 105. Via

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119a, 119b of <sup>the</sup> diffusion barriers is formed in the via hole. The plug is thus connected with the layered interconnect formed previously. Via the plug, a second layered interconnect that comprises a conductor film 123 ~~as~~ coated with neighboring films 122a, 122b of <sup>the</sup> diffusion barriers is connected with the conductor film 117. The second layered interconnect is formed, for example, by forming trenches for interconnection in an insulating film 124, then forming the neighboring film 122a at the bottom of each trench, for example, through chemical vapor deposition, forming the conductor film 123 on the film 122a, and further forming the neighboring film 122b on the film 123, for example, through chemical vapor deposition. The second layered interconnect may be formed before the insulating film 124 is formed. The conductor film 123 may be formed first through physical vapor deposition ~~in~~ <sup>to</sup> some degree, and thereafter, <sup>completed</sup> according to a different film-forming method (of, for example, plating or chemical vapor deposition). For forming the plug of the conductor film 120 as coated with the neighboring films 119a, 119b, and the second layered interconnect, another process may be employed which comprises forming trenches in the insulating films 121, 124, then forming the neighboring films 119a, 119b and the neighboring film 122a all at <sup>one</sup> ~~a~~ time, and thereafter, forming the conductor film 120 and the conductor film 123. <sup>The</sup> ~~An~~ insulating film 125 is, for example, a silicon oxide film.

In the third embodiment, at least one of the conductor film 117 as coated with the neighboring films 116a, 116b, and the conductor film 123 as coated with the neighboring films 122a, 122b shall be formed of a combination of materials that satisfies an inequality of  $\{A + B \times (a_p/b_p)\} < 13$ , where A indicates the difference between the short side,  $a_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring films and the short side,  $a_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film, and is represented as  $\{|a_p - a_n|/a_p\} \times 100 = A (\%)$ , and B indicates the difference between the long side,  $b_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring films and the long side,  $b_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film, and is represented as  $\{|b_p - b_n|/b_p\} \times 100 = B (\%)$ . This is for the purpose of retarding the diffusion of the conductor film so as to prevent voids that may be caused by so-called electromigration. Concretely, for example, where the conductor film 117 is a copper (Cu) film; the neighboring films 116a, 116b could be any <sup>film</sup> ~~one~~ selected from the group consisting of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film, an osmium (Os) film and a platinum (Pt) film. Since the conductor films 115, 120 for the plugs are adjacent to the conductor film 117, they could be considered as the neighboring films to the conductor film

Film

Film

(Rh)

to the conductor films 115, 120. Though not shown in Fig. 8, any one or more additional layers may be formed between each of the neighboring films 116a, 116b, 122a, 122b, 114a, 114b, 119a, 119b and the insulating film adjacent thereto, <sup>Seen</sup> as in Fig. 7.

Though not <sup>shown</sup> in Fig. 8, it is desirable to provide a diffusion barrier also on the side walls of the conductor film 117 and the conductor film 123, in order to prevent atoms from diffusing into the insulating films through the side walls of the conductor films 117, 123.

The invention is not limited to only interconnects, diffusion barriers and plugs, but could apply to electrodes.

For example, where the gate electrodes 108, 109 have a layered structure that comprises a conductor film and a neighboring film, they may be formed of a combination of materials that satisfies an inequality of  $\{A + B \times (a_p/b_p)\} < 13$ , in which A indicates the difference between the short side,  $a_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring film and the short side,  $a_p$ , of the rectangular unit cells that constitute the plane with minimum free energy of the conductor film, and is represented as  $\{|a_p - a_n|/a_p\} \times 100 = A (\%)$ , and B indicates the difference between the long side,  $b_n$ , of the rectangular unit cells that constitute the plane with minimum free energy of the neighboring film and the long side,  $b_p$ , of the rectangular unit cells that



constitute the plane with minimum free energy of the conductor film, and is represented as  $\{|b_p - b_n|/b_p\} \times 100 = B (\%)$ . This is for the purpose of retarding the diffusion of the conductor film so as to prevent voids that may be caused by so-called electromigration. Concretely, for example, where the conductor film is a copper (Cu) film, the neighboring film could be any ~~one~~<sup>film</sup> selected from the group consisting of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film, an osmium (Os) film and a platinum (Pt) film. Where the conductor film is a platinum (Pt) film, the neighboring film could be any ~~one~~<sup>Film</sup> selected from the group consisting of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film and an osmium (Os) film. If desired, an additional film of titanium nitride or the like may be provided between the gate electrodes 108, 109 and the gate-insulating films 106, 107.

In the embodiments mentioned above, where a copper (Cu) film is used for the conductor film, any ~~one~~<sup>Film</sup> selected from the group consisting of a rhodium (Rh) film, a ruthenium (Ru) film, an iridium (Ir) film, an osmium (Os) film and a platinum (Pt) film ~~is~~<sup>may be</sup> used for the neighboring film for retarding the copper diffusion. Of those, a ruthenium (Ru) film will be the best for the neighboring film, ~~as having~~<sup>since it has</sup> a high melting point and ~~being~~<sup>is</sup> easy to work.

Fig. 9 is referred to, which shows one preferred functional structure of the semiconductor device of the third embodiment.

The structural difference between Fig. 9 and Fig. 8 is that, in Fig. 9, a neighboring film 126a is formed between the neighboring film 116a and the insulating film 113, a neighboring film 126b is formed between the neighboring film 116b and the insulating film 121, a neighboring film 127a is formed between the neighboring film 122a and the insulating film 121, and a neighboring film 127b is formed between the neighboring film 122b and the insulating film <sup>125.</sup> ~~121~~. The conductor films 117, 123

<sup>which are</sup> ~~to be~~ interconnects are copper (Cu) films having a low electric resistance, in order that the device could have good capabilities for rapid operation. In order to make the copper (Cu) film interconnects have good electromigration resistance, the neighboring films 116a, 116b, 122a, 122b of diffusion barriers for the copper (Cu) films 117, 123 are ruthenium (Ru) films. The plugs 115, 120 adjacent to the copper (Cu) films 117, 123 are ruthenium (Ru) films so as to have good electromigration resistance. Electromigration resistance is especially important near plugs, for example, as in <sup>discussed</sup> "Materials Reliability in Microelectronics", pp. 81-86 in Vol. 428 of *Symposium Proceedings of the Materials Research Society (MRS)*.

The ruthenium (Ru) plugs have the advantage of good resistance against heat. In that <sup>regard</sup> ~~constitution~~, the plug 115 and the diffusion barrier 116a are both ruthenium (Ru) films, and it is desirable to form these films both at <sup>the same</sup> ~~a time as facilitating~~ <sup>to facilitate</sup>

<sup>Similarly,</sup> ~~Like these~~, the plug 120 and the diffusion

Q

[illegible]

including different temperatures, etc.

Fig. 6 shows rectangular unit cells that <sup>constitute</sup> ~~constitutes~~ the crystal plane with minimum free energy in a bulk crystal, in which the short side,  $a$ , and the long side,  $b$ , of the rectangular unit cell are defined. This is described in more detail hereinunder. The short side,  $a$ , indicates the interatomic distance between the nearest neighbors in a bulk crystal, which

is referred to, for example, in a Japanese translation of *Introduction to Solid State Physics*, Part I, 5th Ed. (written by Charles Kittel, published by Maruzen in 1978), page 28. The long side,  $b$ , is about 1.73 times the short side,  $a$ , in crystals with the face-centered cubic structure or the hexagonal close-packed structure, but is about 1.41 times the short side,  $a$ , in crystals with the body-centered cubic structure. For example, the plane with minimum free energy of copper (Cu) having the face-centered cubic structure is the (111) plane, and its short side,  $a_{Cu}$ , is about 0.26 nm, while its long side,  $b_{Cu}$ , is about 0.44 nm. The plane with minimum free energy of ruthenium (Ru) having the hexagonal close-packed structure is the (001) plane, and its short side,  $a_{Ru}$ , is about 0.27 nm, while its long side,  $b_{Ru}$ , is about 0.46 nm.

Based on the results of the invention as <sup>described</sup> above, we, the inventors, have made researches <sup>into</sup> ~~about~~ related techniques. As a result, we have found JP-A-10-229084 relating to copper (Cu) interconnects and diffusion barriers for them. However, this obviously differs from the present invention for the following reasons. Specifically, JP-A-10-229084 is directed to a technical theme for easy formation of a diffusion barrier and a copper (Cu) film interconnect in contact holes having a high aspect ratio, and its ~~subject matter~~ <sup>object</sup> is to construct an interconnect structure by forming both the diffusion barrier and the copper (Cu) film interconnect through plating or

chemical vapor deposition (CVD), but not through physical vapor deposition (PVD), such as sputtering or the like. Being different from this, the present invention is directed to an interconnect structure for which at least one of a diffusion barrier and a copper (Cu) film interconnect is formed through physical vapor deposition, like those for ordinary interconnect structures. The <sup>object</sup>~~subject matter~~ of the present invention is to improve the electromigration resistance, which is especially important for films formed through physical vapor deposition. For an ordinary diffusion barrier and a copper (Cu) film interconnect, at least one of them is formed through physical vapor deposition, such as sputtering or the like, for example, <sup>discussed</sup> as in a monthly journal, *Semiconductor World* (for February 1998, pp. 91-96, published by Press Journal). As so described therein, for forming a copper (Cu) film interconnect through plating or <sup>a method is</sup> chemical vapor deposition (CVD), generally employed ~~is a method~~ comprising previously forming a seed layer for a copper (Cu) film through physical vapor deposition (PVD), such as sputtering or the like, which is then switched to plating or chemical vapor deposition (CVD) to complete the intended copper (Cu) film interconnect. Therefore, the method proposed in JP-A-10-229084, in which both a diffusion barrier and a copper (Cu) film interconnect are formed through plating or chemical vapor deposition (CVD), but not through physical vapor deposition (PVD), such as plating or the like, will be favorable to the object

a a

a  
a  
a

For example, the neighboring films 116a, 116b as provided adjacent to the conductor film 117 of copper (Cu) are diffusion barriers. However, the diffusion barrier may act for improving adhesiveness, or for controlling crystal orientation or even for controlling grain size, and, as the case may be, its primary role is often not for diffusion retardation. In the present specification, the neighboring films with conductivity, such as 116a, 116b, 114a, 114b that are provided adjacent to conductor films are all referred to as diffusion barriers, even though they act for other ~~objects but~~ <sup>purposes and</sup> not for diffusion retardation only.

The copper (Cu) film referred to herein indicates a film for which the primary constituent element is copper (Cu) <sup>but</sup> ~~and~~ it may additionally contain any other elements. With such other elements, the film could still exhibit the same effects as herein. The same shall apply to the ruthenium (Ru) film and others referred to therein.

While the invention has been described in detail and with reference to specific embodiments thereof, it will be apparent to one skilled in the art that various changes and modifications can be made therein without departing from the spirit and scope thereof.